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WIND TUNNEL PRESSURE DISTRIBUTION TESTS ON A SERIES OF BIPLANE WING MODELS

PART III. EFFECTS OF CHANGES IN VARIOUS COMBINATIONS OF STAGGER, GAP, SWEEPBACK AND DECALAGE

By Montgomery Knight and Richard W. Noyes
Langley Memorial Aeronautical Laboratory

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A CONCEPT OF THE VORTEX LIFT OF SHARP-EDGE DELTA WINGS BASED ON A LEADING-EDGE-SUCTION ANALOGY

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A CONCEPT OF THE VORTEX LIFT OF SHARP-EDGE DELTA WINGS BASED ON A LEADING-EDGE-SUCTION ANALOGY

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SUMMARY

A concept for the calculation of the vortex lift of sharp-edge delta wings is presented and compared with experimental data. The concept is based on an analogy between the vortex lift and the leading-edge suction associated with the potential flow about the leading edge. This concept, when combined with potential-flow theory modified to include the nonlinearities associated with the exact boundary condition and the loss of the lift component of the leading-edge suction, provides excellent prediction of the total lift for a wide range of delta wings up to angles of attack of 20° or greater.

INTRODUCTION

The aerodynamic characteristics of thin sharp-edge delta wings are of interest for supersonic aircraft and have been the subject of theoretical and experimental studies for many years in both the subsonic and supersonic speed ranges. Of particular interest at subsonic speeds has been the formation and influence of the leading-edge separation vortex that occurs on wings having sharp, highly swept leading edges. In general, this vortex flow results in an increase in lift associated with the upper-surface pressures induced by the vortex and an increase in drag resulting from the loss of leading-edge suction. Although, in general, it is desirable to avoid the formation of the separation vortex because of the high drag, it is sometimes considered as a means of counteracting, to some extent, the adverse effect of the low lift-curve slope of delta wings with regard to the landing attitude.

In recent years, the interest in the vortex flows associated with thin delta and delta-related wings has increased considerably as a result of the supersonic commercial air transport programs that are underway both in this country and abroad. Even though several theoretical methods of predicting the effects of separation vortex flows on the lift of delta wings have been developed, there appears to be no completely satisfactory method – especially when angles of attack and aspect ratios of practical interest are considered. The purpose of the present paper, therefore, is to present a concept with regard to vortex flow which appears to circumvent the problems encountered in the previous methods. In

this concept, the pressures required to maintain the flow about the leading-edge vortex are related to those required to maintain potential flow about the leading edge.

SYMBOLS

A wing aspect ratio, b^2/S

b wing span

C_{Di} theoretical induced-drag coefficient

C_L total lift coefficient, $C_{L,p} + C_{L,v}$

$C_{L,p}$ lift coefficient determined by linearized potential-flow theory (present application does not include leading-edge-suction component)

$C_{L,v}$ lift coefficient associated with leading-edge separation vortex

$C_{N,p}$ normal-force coefficient determined by linearized potential-flow theory

$C_{N,v}$ normal-force coefficient associated with leading-edge separation vortex

C_p upper-surface pressure coefficient

C_S leading-edge suction coefficient (in plane of wing and perpendicular to leading edge)

C_T leading-edge thrust coefficient (in plane of wing and parallel to flight direction)

K_i induced-drag parameter, $\partial C_{Di}/\partial C_L{}^2$

K_p constant of proportionality in potential-flow lift equation

K_v constant of proportionality in vortex lift equation

L lift

N normal force

S wing area

T thrust force (in plane of wing and parallel to flight direction)

V velocity in flight direction

w_i average downwash velocity induced by trailing vortex sheet (perpendicular to wing chord)

α	angle of attack
Γ	total effective circulation
Λ	leading-edge sweep angle
ρ	mass density of air

DISCUSSION AND RESULTS

Nonlinear Lift Characteristics

Wind-tunnel studies of sharp-leading-edge delta wings have shown that even at relatively low angles of attack the flow separates from the leading edges and rolls up into two vortex sheets or cone-shaped cores of rotating fluid, as illustrated in figure 1. Flow attachment lines have been observed inboard of the vortex sheets and indicate that air is drawn over the vortex sheets and accelerated downward. An increase in lift at a given angle of attack results and it is this increase that is usually referred to as nonlinear or vortex lift. Many flow visualization photographs have been obtained by various researchers which substantiate the general nature of the flow illustrated by the sketch in figure 1. One such photograph, obtained from wind-tunnel tests (ref. 1), is shown in figure 2(a) and illustrates, by means of smoke filaments, the spiral vortex flow associated with a 60° delta wing at an angle of attack of 12°. This spiral vortex flow has also been observed in flight, as illustrated by the photograph of a landing of the XB-70 airplane (fig. 2(b)). The flow was made visible by condensation due to the humidity of the atmosphere.

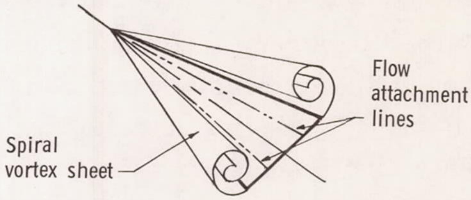
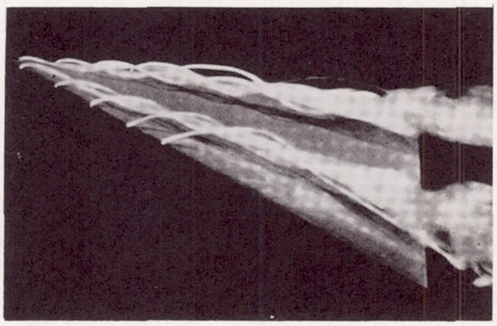
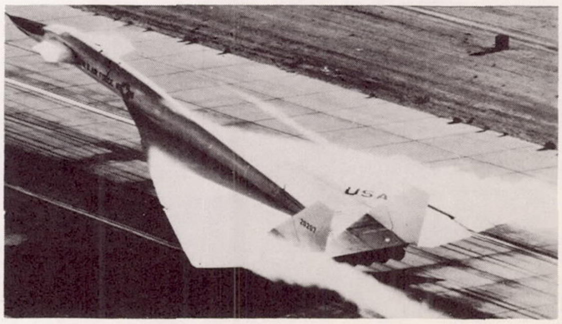


Figure 1.- Illustration of vortex flow.



(a) Wind tunnel (from ref. 1).



(b) Flight.

Figure 2.- Photographs illustrating spiral vortex flow.

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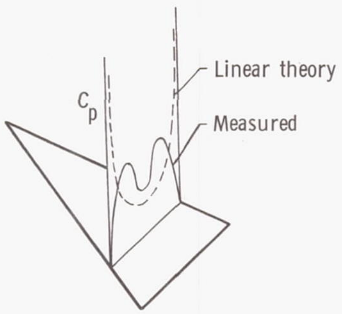

Figure 3.- Theoretical and experimental pressure distributions.

The vortex flow not only increases the lift but changes the distribution of lift rather drastically, as illustrated in figure 3 where typical measured spanwise pressure distributions at one longitudinal station are compared with distributions calculated from potential-flow theory (ref. 2, for example). (Complete surface pressure distributions can be obtained from refs. 3, 4, and 5.) Because of the flow separation at the sharp leading edge, the pressure peaks at the leading edges predicted by potential-flow theory are not developed, but peaks are developed inboard of the leading edges due to the separated vortex sheets.

Previous Methods

Many methods have been developed for estimating the effect of the separated vortex sheets with varying degrees of success. For the purpose of this study, most of the previous methods for delta wings can be separated into the two general approaches illustrated in figure 4. The first general approach follows the work of Bollay for rectangular wings (ref. 6) and assumes that the vorticity shed ahead of the trailing edge is displaced at an angle, relative to the flight direction, equal to one-half the angle of attack. This displacement reduces the downwash induced at the wing surface and thereby requires additional circulation in order to maintain the boundary condition of tangential flow at the wing surface. The application to arbitrary planform wings has been carried out by Gersten (ref. 7) who replaced the wing with infinitesimal lifting elements, applied Bollay's mathematical model to each lifting element, and solved for the surface load distribution required to satisfy the boundary condition by using the method of Truckenbrodt (ref. 8). The second general approach replaces the two spiral vortex sheets with two concentrated line vortices above the wing and two feeding vortex sheets connecting the leading edge (source of the vorticity) and the line vortices. Several degrees of approximation to the shape of the real

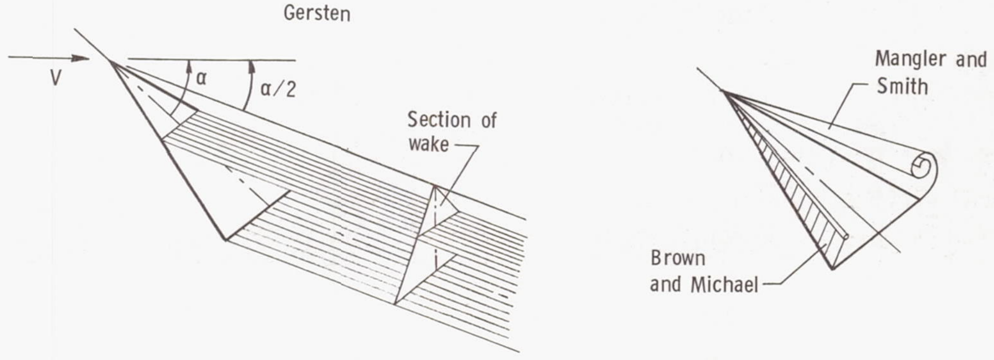

Figure 4.- Theoretical approaches to vortex-flow calculations.

spiral vortex sheets within this general approach have been made. Brown and Michael (ref. 9), for example, use isolated vortices and planar feeding sheets. Mangler and Smith (ref. 10) have improved on this model by a calculation of an approximate form of the vortex sheet between the wing leading edge and a point not too distant from the center of the spiral.

The results obtained from the aforementioned methods are compared in figure 5, where the total lift coefficient for an angle of attack of 15° is presented as a function of aspect ratio. In addition, the experimental values for sharp-leading-edge delta wings (obtained from refs. 4 and 11 to 14) are presented to assist in evaluating the various theoretical methods. It is, of course, recognized that several of the methods assume low angles of attack and are based on slender-body theory. However, inasmuch as this paper is concerned primarily with the prediction of the lift at the relatively high angles of attack encountered during the landing of supersonic vehicles, an angle of attack of 15° was selected for the comparisons. The correlation is presented as a function of aspect ratio in order to enable an evaluation in the not-so-slender-wing range of interest for vehicles designed to cruise at Mach numbers of 3.0 or less. As might be expected, the theory of Gersten (solid-line curve) results in the best correlation with regard to the variation with aspect ratio since it is not limited to slender wings. However, Gersten's method predicts only about one-half the actual vortex lift for the conditions of interest in this study. The approach of Brown and Michael, although more representative of the actual vortex flow conditions than the Gersten approach, gives extremely high values of vortex lift even in the low-aspect-ratio range for which the slender-wing theory should be most applicable. A correction to the linear part to account for nonslender effects would result in only small improvements. The method of Mangler and Smith provides the most realistic flow model and results in considerable improvement over the method of Brown and Michael, particularly in the low-aspect-ratio range where the slender-body theory is most applicable. However, for aspect ratios above about 0.7, this method departs rather rapidly from the experimental values and is not appropriate for the present application.

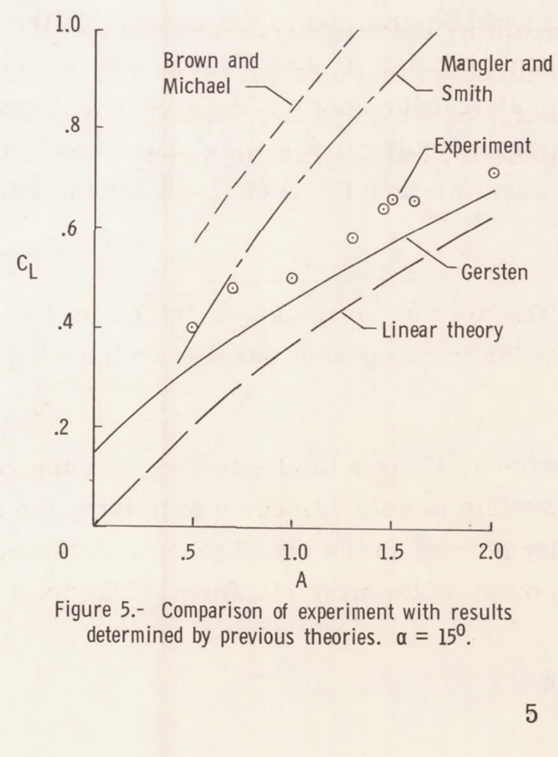

Figure 5.- Comparison of experiment with results determined by previous theories. $\alpha = 15^{\circ}$.

There have been several recent attempts to improve on these methods. Pershing (ref. 15) has attempted to account for the secondary vortex system by modifying the boundary conditions; however, this method departs radically from experiment at low aspect ratios despite the fact that slender-body techniques are

used. Reference 16 describes some preliminary studies of a theoretical approach, requiring a high-speed computer, in which vortices shed from the leading edge are allowed to interact and roll up. This general approach might ultimately provide a method of predicting details of the flow; however, in the initial application described in reference 16, this theory appears to depart from experiment to a degree similar to that of reference 10.

Present Method

The present approach assumes that if flow reattachment occurs on the upper surface the total lift can be calculated as the sum of a potential-flow lift and a lift associated with the existence of the separated leading-edge spiral vortices. First, the potential-flow lift will be examined with regard to the effect of high angles of attack and modified leading-edge conditions. Then, the vortex lift will be determined by a method in which the vortex flow is assumed to be related to the potential flow about the leading edge.

Potential lift.- Inasmuch as potential-flow theory is usually presented in a form applicable only for wings at low angles of attack, the development of the theory in a form more applicable for the high angles of attack of interest in the present study will be used. In addition, the potential-flow theory must be modified for application to the leading-edge separation condition for the sharp-edge delta wings considered in this paper. In order to account for the leading-edge separation, a Kutta type flow condition is assumed to exist at the sharp leading edge and, therefore, no leading-edge suction can be developed. It is further assumed, since the flow reattaches downstream of the separation vortex, that the potential-flow lift is diminished only by the loss of the lift component of the leading-edge suction. Although, logically, the loss of the lift component of the leading-edge suction should be charged to the vortex-lift term, it is more convenient in the present concept to consider this loss as a modification to the potential-lift term. For the condition of zero leading-edge suction, the resultant force (neglecting friction drag) for the planar wings is perpendicular to the wing chord and is equal to the potential-flow normal force. The potential-flow lift coefficient for the zero-leading-edge-suction condition is given by

$$C_{L,p} = C_{N,p} \cos \alpha \tag{1}$$

The normal force can be determined by applying the Kutta-Joukowski theorem using the velocity component parallel to the wing chord; thus,

$$N = \rho \Gamma b(V \cos \alpha) \tag{2}$$

where Γ is a total effective circulation. The distribution of circulation in the lifting system is determined by satisfying the boundary condition which requires that the velocity normal to the chord plane induced by the total vortex system be equal to $V \sin \alpha$ at points on the wing planform. The total effective circulation can then be written as

$$\Gamma = K_p \frac{SV}{2b} \sin \alpha \tag{3}$$

Since, for the wings of interest herein, departures of the potential-flow vortex system from the wing plane and its extension would be expected to have negligible effect on Γ, it is assumed that K_p depends only on planform. Substituting equation (3) into equation (2) and reducing the normal force to coefficient form results in

$$C_{N,p} = K_p \sin \alpha \cos \alpha \tag{4}$$

The potential-flow lift coefficient for the condition of zero leading-edge suction[1] can now be determined by substituting the expression for $C_{N,p}$ (eq. (4)) into equation (1); thus,

$$C_{L,p} = K_p \sin \alpha \cos^2\alpha \tag{5}$$

Since K_p depends only on planform and equation (5) reduces to $C_{L,p} = K_p\alpha$ for small angles of attack, it is apparent that K_p is equal to the lift-curve slope given by small-angle theory and can therefore be determined from any suitable lifting-surface theory. In this paper, K_p is determined by a modification[2] of the Multhopp lifting-surface theory of reference 17. The variation of K_p with aspect ratio is presented in figure 6.

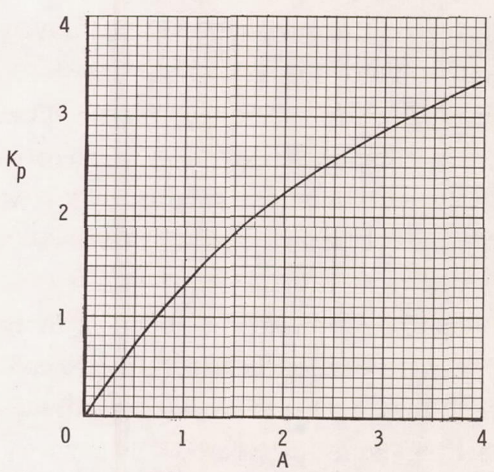

Figure 6.- Variation of K_p with A for delta wings.

Vortex lift.- The major problem associated with the prediction of the lift of sharp-edge delta wings is, of course, the calculation of the so-called vortex lift associated with the leading-edge-separation spiral vortex. This problem arises primarily from the difficulty in determining with sufficient accuracy the strength, shape, and position of the spiral vortex sheet and it is in this area that the present method differs from previous approaches.

In the present method an attempt to avoid the various problems associated with the calculation of the strength, shape, and position of the spiral vortex sheet is made by relating the force required to maintain the equilibrium of the flow over the separated spiral vortex (provided that the flow reattaches on the upper surface) with the force associated with the theoretical leading-edge singularity for thin wings in potential flow. Figure 7 shows pictorial sketches, in a plane normal to the leading edge, of the potential flow about a sharp leading edge and a round leading edge and the separated vortex flow about a sharp leading edge.

[1] For full leading-edge suction, the nonlinear effects in potential-flow theory can be determined from $L = \rho \Gamma b(V - w_i \sin \alpha)$, where Γ is obtained from equation (3) and $w_i \sin \alpha$ accounts for the reduction of the relative velocity in the flight direction due to the inclined vortex system.

[2] The modifications to the Multhopp theory include the extension to higher order chordwise loading terms as developed by Van Spiegel and Wouters (ref. 18) and refinements in the numerical integration procedure developed by John E. Lamar of the Langley Research Center.

For the attached flow condition, the flow ahead of the lower-surface stagnation point flows forward and is accelerated around the leading edge to the top surface. The pressure required to balance the centrifugal force created by the flow about the leading edge results, of course, in the leading-edge suction force. As the leading-edge radius is increased, the potential-flow suction force remains essentially constant since the suction pressures vary inversely as the leading-edge radius. (See ref. 2.) As shown in the sketch representing the separated flow about the sharp leading edge (fig. 7(c)), the flow ahead of the stagnation point flows forward but separates from the wing as it leaves the leading edge tangentially and rolls up into the previously discussed spiral vortex sheet. (See fig. 1.) Air is drawn over this vortex sheet and accelerated downward to an upper-surface flow attachment line. Since the flow over the vortex sheet reattaches, the basic assumption of the present method is that the total force on the wing associated with the pressures required to maintain the equilibrium of the flow over the separated spiral vortex sheet is essentially the same as the leading-edge suction force associated with the leading-edge pressures required to maintain attached flow around a large leading-edge radius. The flow pattern in both cases would be somewhat similar, as indicated by comparing figures 7(b) and 7(c); however, for the sharp-leading-edge condition, the force acting on the wing will act primarily over the upper surface rather than on the leading edge. Therefore, a normal force occurs which is equal to the theoretical leading-edge suction force. (See fig. 7(c).) Since the theoretical leading-edge suction force is essentially independent of leading-edge radius, the normal force associated with the separated spiral vortex sheet should be equivalent to the leading-edge suction force as predicted by an appropriate thin-wing lifting-surface theory. (It must be kept in mind that this force is the resultant perpendicular to the leading edge and not that component parallel to the flight direction.) Both suction forces are in the wing chord plane, and the component in the flight direction will be referred to as the leading-edge thrust coefficient C_T and the resultant suction force perpendicular to the leading edge will be referred to as the leading-edge suction coefficient C_S. (See fig. 8.)

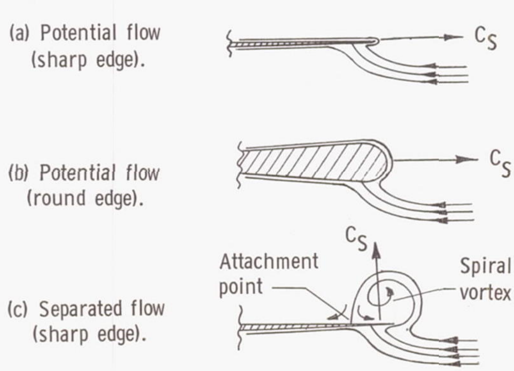

Figure 7.- Leading-edge flow conditions.

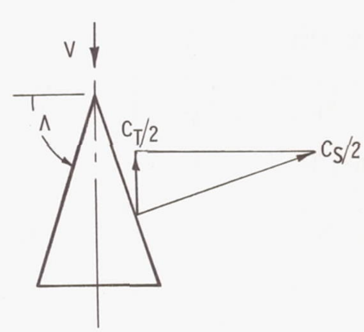

Figure 8.- Relationship between C_T and C_S.

Based on the concept of this paper, the resultant suction force is rotated into a direction normal to the wing chord plane and therefore the normal-force coefficient associated with the leading-edge vortex is given by

$$C_{N,v} = C_S = \frac{C_T}{\cos \Lambda}$$

The lift coefficient can then be given by

$$C_{L,v} = C_{N,v} \cos \alpha = C_T \frac{\cos \alpha}{\cos \Lambda} \tag{6}$$

The problem now reduces to the determination of the thrust coefficient associated with potential flow around the leading edge. By applying the Kutta-Joukowski theorem using velocity components normal to the wing chord plane, the leading-edge thrust is given by

$$T = \rho \Gamma b(V \sin \alpha - w_i) \tag{7}$$

where w_i is an effective downwash velocity induced normal to the chord by the trailing vortex system. The magnitude of w_i is that which will act on the total effective circulation Γ to produce the same induced drag as the actual distributed wake-induced velocity acting on the distributed lifting vortex system. The total effective circulation Γ is given by equation (3) and upon substitution into equation (7) yields, in coefficient form,

$$C_T = \left(1 - \frac{w_i}{V \sin \alpha}\right) K_p \sin^2 \alpha \tag{8}$$

Since w_i is proportional to Γ, which in turn is proportional to $V \sin \alpha$ by virtue of the boundary condition, then it follows that $w_i/V \sin \alpha$ is independent of angle of attack. Therefore, by use of the induced-drag relationships of small-angle theory, it can be shown that

$$\frac{w_i}{V \sin \alpha} = K_p K_i \tag{9}$$

where $K_i = \dfrac{\partial C_{Di}}{\partial {C_L}^2}$.

Substitution of equation (9) into equation (8) gives

$$C_T = \left(K_p - {K_p}^2 K_i\right) \sin^2 \alpha \tag{10}$$

and with the aid of equation (6)

$$C_{L,v} = \left(K_p - {K_p}^2 K_i\right) \frac{\cos \alpha}{\cos \Lambda} \sin^2 \alpha \tag{11}$$

The constant K_i can be determined from any reliable lifting-surface theory, and the modified Multhopp theory described earlier will be used in this paper.

Equation (11) can be rewritten in the form

$$C_{L,v} = K_v \cos\alpha \sin^2\alpha \tag{12}$$

where

$$K_v = \left(K_p - K_p^2 K_i\right)\frac{1}{\cos\Lambda} \tag{13}$$

Values of K_v have been calculated for a series of delta wings by using the lifting-surface theory previously described and the results are presented in figure 9. The value of K_v increases slightly from a value of 3.14 for an aspect ratio of 0 to a value of about 3.45 for an aspect ratio of 4. It should not be concluded from these results that this variation of K_v with aspect ratio is a general result. For example, if the leading-edge sweep is held constant and aspect ratio varied by changing the trailing-edge sweep (such as in arrow and diamond wings), larger variations of K_v will be encountered.

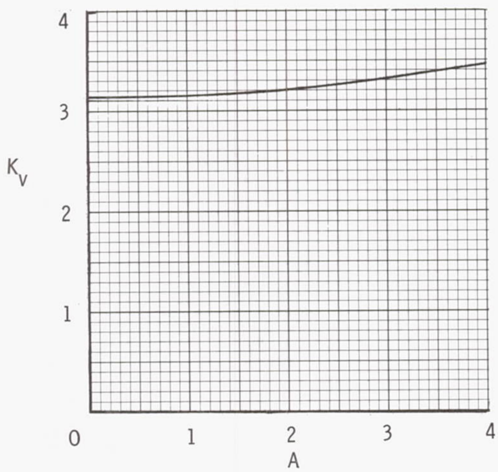

Figure 9.- Variation of K_v with A for sharp-edge delta wings.

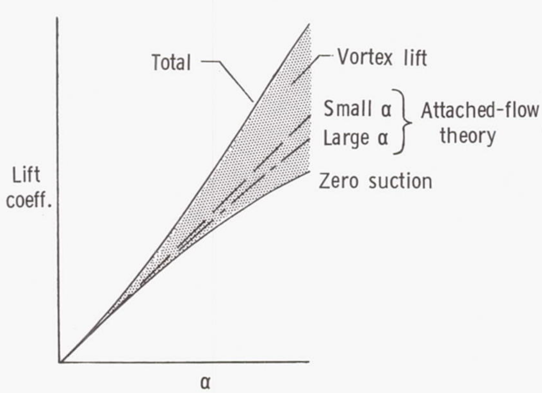

Figure 10.- Contribution of various effects.

Total lift.- The total lift coefficient for delta wings having sharp leading edges can now be obtained by the addition of the potential-lift term (eq. (5)) and the vortex-lift term (eq. (11)) as follows:

$$C_L = K_p \sin\alpha \cos^2\alpha + \left(K_p - K_p^2 K_i\right)\frac{\cos\alpha}{\cos\Lambda}\sin^2\alpha \tag{14}$$

where the constants K_p and K_i can be determined from an appropriate lifting-surface theory. The total lift coefficient can also be determined from

$$C_L = K_p \sin\alpha \cos^2\alpha + K_v \cos\alpha \sin^2\alpha \tag{15}$$

where the constants K_p and K_v are obtained from figures 6 and 9, respectively. Figure 10 illustrates the contribution of the various effects when leading-edge separation is involved. There is a reduction in lift when the trigonometric term in the linear theory is retained, an additional reduction due to the loss of the lift component of the leading-edge suction, and a large increase associated with the vortex induced lift.

Comparison With Experiment

In order to evaluate the accuracy of the present method, comparisons have been made with available experimental data for sharp-edge delta wings of various aspect ratios. The first comparison is presented in figure 11 where the lift coefficient developed at an angle of attack of 15° is presented as a function of aspect ratio. This figure is essentially the same as figure 5 except that the curve based on the present theory has been added. The present theory appears to provide adequate predictions of the lift over the entire aspect-ratio range as indicated by the excellent agreement with the wind-tunnel measurements.

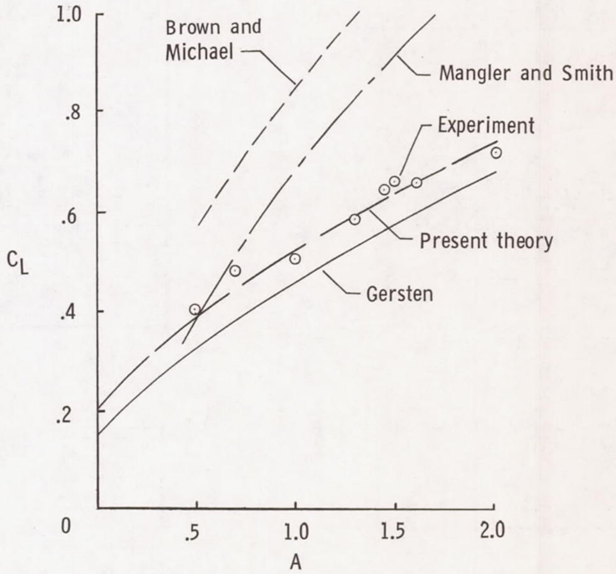

Figure 11.- Comparison of experiment with results determined by present and previous theories. $\alpha = 15^{\circ}$.

In order to evaluate the applicability of the present method more fully, comparisons are made as a function of angle of attack for delta wings of various aspect ratios in figure 12. The angle-of-attack range extends to 25°, which is well beyond the angle usually considered as the maximum permissible approach angle of attack; the aspect ratios cover the range from 0.5 to 2.0, which includes those delta wings of interest for both supersonic and hypersonic vehicles. Excellent agreement is obtained between the present theory and the experimental data for all angles of attack up to about 25° except for the aspect-ratio-2.0 wing, which shows some reduction in lift above an angle of attack of about 18°. This loss is probably associated with trailing-edge separation, which would be expected to be more severe for high aspect ratios because of steeper adverse pressure gradients associated with the larger value of the theoretically available potential lift. In addition to the

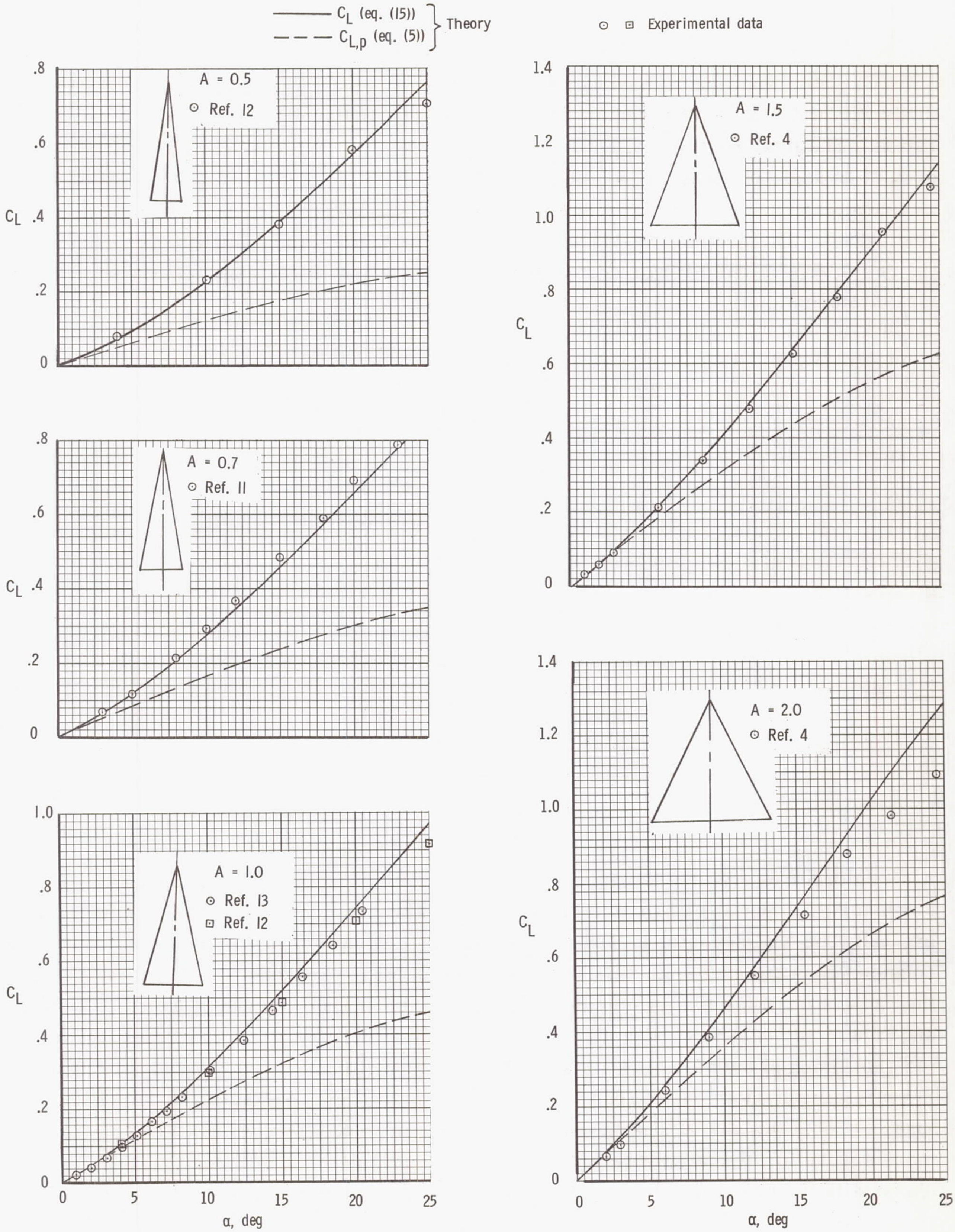

Figure 12.- Comparison of theory with experimental data for sharp-edge delta wings.

predicted values of total lift (shown by the solid lines), the potential-flow lift term with the lift component of the leading-edge suction removed (eq. (5)) is presented (dashed lines) and it will be noted that at the higher aspect ratios the nonlinearity of this term becomes rather significant.

CONCLUDING REMARKS

From the preceding analysis it appears that the proposed equivalence between the vortex lift developed on thin sharp-edge delta wings and the leading-edge suction associated with the potential-flow leading-edge singularity provides a simple and accurate method of predicting the vortex lift over a wide range of angles of attack and aspect ratios. In addition, the analysis indicates that if the nonlinearities in the linearized potential-flow theory associated with the exact boundary condition and the loss of the lift component of the leading-edge suction are included, the total lift can be estimated accurately as the sum of the potential- and vortex-lift estimates.

This proposed analogy provides a simple method of including all interacting effects of such items as the wing and wake induced flows along the leading edge which have created difficulties in previous methods and should simplify the predictions for other planforms such as the double delta. It should be emphasized, however, that a rigorous theoretical proof of the concept has not, as yet, been established. Such proof or additional experimental checks will be required before this concept can be confidently used to predict the lift for planforms other than the conventional delta wings considered in the present study. Application of the concept to pitching moments will probably require modification of the chordwise distribution of the potential term as well as an accurate prediction of the distribution of the vortex lift. Adequate estimation of the drag due to lift should be obtained from the product of the total lift coefficient and the tangent of the angle of attack.

Although the present investigation was limited to low subsonic speeds, it is apparent that the leading-edge suction analogy, when applied at supersonic speeds, will predict a reduction in vortex lift with increasing Mach number and a complete elimination of vortex lift when the Mach line coincides with the leading edge.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 17, 1966,
126-13-01-50-23.

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